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# ANTHROPOGENIC INFLUENCES ON THE PERSISTENT NIGHT-TIME HEAT WAVE IN SUMMER 2018 OVER NORTHEAST CHINA

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Persistent night-time heat waves like the event of summer 2018 in Northeast China are extremely rare (about a one-in-a-500-year event) in the natural world, but now have become about a one-in-60-year event with anthropogenic warming.

In the summer of 2018, Northeast China was affected by an unprecedentedly long and intense heat wave. The China Meteorological Administration issued 33 days of consecutive "high temperature-alert" warnings from 14 July to 15 August in 2018. Record-breaking hot minimum temperatures were observed in a large area of Northeast China (34°–55°N, 105°–135°E) with a stable spatial pattern on time scales of 20–40 days (Fig. 1a; see also Fig. ES1 in the online supplemental material). Further, minimum temperatures were more extreme, with a much larger record-breaking area than maximum temperatures (Fig. ES1). On 30 July, the number of heat-related hospitalization admissions broke the historical record in Shenyang, a large city in Northeast China (http://news.lnd.com.cn/system/2018/08/01/000008645.shtml). The aquaculture industry in Liaoning Province suffered from economic loss of 6.87 billion renminbi (RMB) (www.zhonghongwang.com/show-256-103674-1.html). Thus, this unprecedented persistent and extreme heat wave event led to severe impacts, including increased human morbidity and mortality, reduced agriculture productivity, and increased strain on power systems and water supplies.

Anthropogenic warming has been shown to drive recent record-breaking heat and summer extremes in different regions of the world (Hansen et al. 2012; Lewis and Karoly 2013). Previous heat event attribution studies in China usually considered seasonal mean and maximum temperature covering a fixed period (e.g., Sun et al. 2016a; Ma et al. 2017), with few studies focusing on consecutive minimum temperatures when there is the strongest signal in summer. Daily minimum temperature allows people and ecosystems to recover from thermal stresses experienced during the previous day (Schwartz 2005) and is a strong predictor for human morbidity and mortality (Laaidi et al. 2012; Madrigano et al. 2015; Murage et al. 2017). Previous studies show that anthropo-

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genic influences, including anthropogenic emission of greenhouse gases and urbanization leading to the expansion of urban heat islands, has contributed to higher summer minimum temperatures in Eastern China (Sun et al. 2016b; Wang et al. 2017). Hence, this study aims to investigate whether anthropogenic influences have increased the frequency of the monthly time scale heat waves like the summer 2018 event over Northeast China.

**DATA AND METHODS.** *Observations.* We used observed daily minimum temperatures at about 2,400 meteorological stations over China for the period 1961–2018. These were quality-controlled and homogenized by National Meteorological Information Center of China (Ren et al. 2012). We also used daily atmospheric circulation field data from ERA-Interim (Dee et al. 2011), including geopotential height, horizontal wind, and specific humidity.

*Model.* Simulations from the atmosphere model HadGEM3-A-N216 at a horizontal resolution of 0.56° × 0.83° were used in this study (Christidis et al. 2013; Ciavarella et al. 2018). Three ensembles were used:

- An 15-member ensemble of simulations for period 1960–2013, in which the model is forced by observed sea surface temperatures (SST) and sea ice concentrations (SIC) from HadISST (Rayner et al. 2003), and a comprehensive package of historical anthropogenic atmospheric forcing (Historical).
- A 525-member ensemble of simulations for 2018 only (counterfactual world), driven with pre-industrial atmospheric forcing and the anthropogenic contribution removed from SST and SIC (HistoricalNatExt; see the online line supplemental information for details).
- A second 525-member ensemble of simulations (factual world), driven as for "Historical" but for 2018 only (HistoricalExt).

*Event definition.* An index of 30-day moving average of daily minimum temperature anomalies (TNx30) over the study area was defined. First, to remove the seasonal cycle at each station, daily minimum temperature ($T_{min}$) anomalies relative to the daily 1961–2013 climatology were computed in each calendar day. We then gridded these anomalies to the 0.56° × 0.83° model resolution by averaging all station anomalies in each grid box. The gridded $T_{min}$ anomalies were then area averaged over Northeast China (34°–55°N,

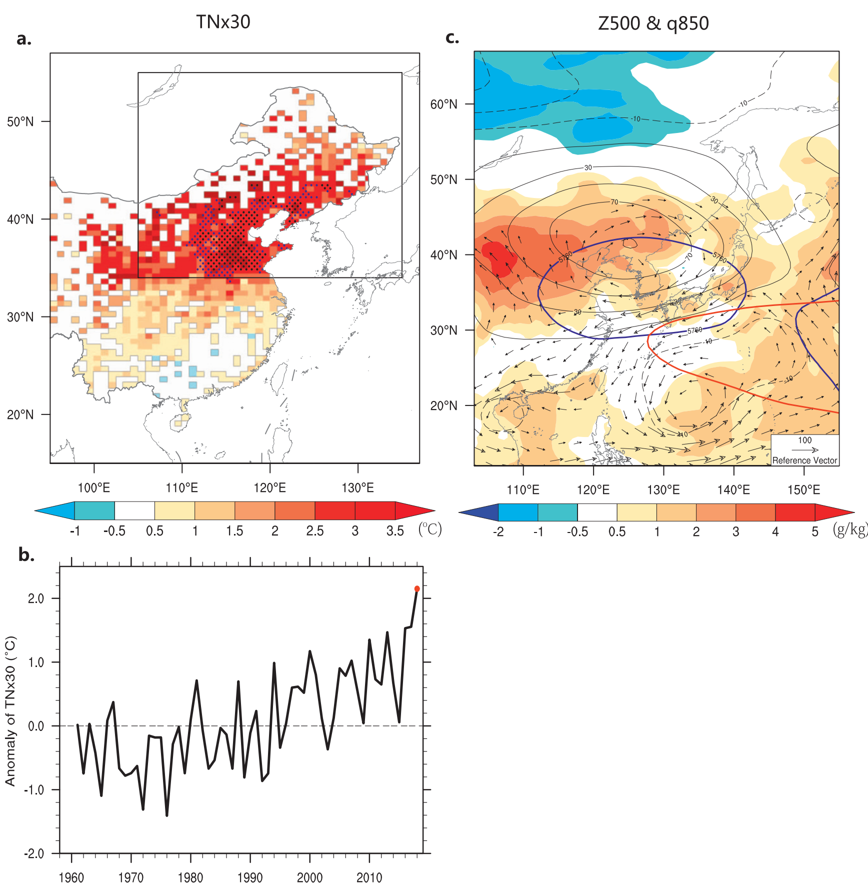


**FIG. 1. Observed characteristics of the heat wave in Northeast China during 12 Jul–10 Aug 2018, with maximum consecutive 30-day Tmin anomalies in summer 2018 (TNx30). (a) Spatial pattern of TNx30 (shading; unit: °C) relative to 1961–2013. Locations with record-breaking and second highest values since 1961 are shown with black and blue dots, respectively. (b) Time series of TNx30 anomalies over Northeast China (black rectangle shown in Fig. 1a) from 1961 to 2018. (c) Circulation field from ERA-Interim with specific humidity anomalies (shading; unit: g kg$^{-1}$) and 850-hPa moisture flux anomalies (vectors). The light black contours denote the 500-hPa geopotential height anomalies. The 12 Jul–10 Aug 2018 mean geopotential height (blue lines) and climatology (red lines) are also shown.**

105°–135°E), and finally used to calculate the hottest 30-day running mean $T_{min}$ in summer (June–August) for each year. For model datasets, the same process was followed except rather than gridding the simulations, grid points were used only if they were land and there were observations in the grid box. The anomaly of the index TNx30 in summer was used in this study and the value of 2018 event (2.15°C) was chosen as the threshold.

To estimate probabilities, generalized extreme value (GEV) distributions were fitted to both simulated and observed data. A two-sided Kolmogorov–Smirnoff (K-S) test was then applied to test if the distributions of the observations and historical simulations from 1961 to 2013 are from the same population. To estimate the anthropogenic contribution to the heat wave event like 2018 summer in Northeast China, the risk ratio (National Academies of Sciences, Engineering, and Medicine 2016) defined as $P$(HistoricalExt)/$P$(HistoricalNatExt) was calculated, where $P$(HistoricalExt) and $P$(HistoricalNatExt) are the probability of the event in factual and counterfactual world, respectively. We bootstrapped with replacement 1,000 times to generate PDFs, and then computed 1,000 risk ratios and then used that to compute uncertainties in risk ratios.

**RESULTS.** *Observed events and model performance.* In summer 2018, the regional average of TNx30 over Northeast China was 3 standard deviations of interannual variability above the 1961–2013 climatology and the highest on record since at least 1961 (Fig. 1b). This heat wave was accompanied by positive geopotential height anomalies over Northeast Asia, induced by the unprecedented northward shift of the western Pacific subtropical high (Fig. 1c; Liu et al. 2019). At low levels (850 hPa), anomalous northwestward moisture transportation from the warm Bohai Sea resulted in increased specific humidity (Fig. 1c) and consequently contributed to significant nighttime warming.

Model performance was evaluated using the ensemble mean of the historical ensemble, which reasonably reproduced the time series of TNx30 anomalies, with a correlation coefficient of 0.70 (Fig. 2a). This means that forcing, SST, and SIC variations explain about half of the observed variance in TNx30. The distributions of observed and simulated TNx30 for summers during 1961–2013 are also statistically indistinguishable based on the K-S test ($p = 0.80$; Fig. 2b). Such good performance of the HadGEM3-A-N216 simulations provides the basis for further attribution analysis.

*Anthropogenic impact on the risk of heat waves.* There is a shift of the PDF to warm anomalies from HistoricalNatExt to HistoricalExt (Fig. 2c), indicating that anthropogenic influences have increased the probability of heat wave events. Since the magnitude of this event lies at the far warm-end tail of PDF, events like 2018 are very rare in the counterfactual world. Only one member in 525-member HistoricalNatExt ensemble exceeds the 2018 threshold. By contrast, the estimated probability is 0.02 in factual world. These indicate that the 2018-like night-time heat event is extremely rare without anthropogenic warming. The estimated return period of heat wave events hotter than 2018 is about one-in-60-years with anthropogenic warming, with 5th–95th percentile uncertainty ranges of 43–116 years (Fig. 2d). A second threshold was also selected, defined as the second-most extreme year (2017, with an anomaly of 1.55°C). For this threshold, the heatwave is 57 times more frequent in the factual world ($P$(HistoricalExt) = 0.17) than the counterfactual world [$P$(HistoricalNatExt) = 0.003], which confirms the role of anthropogenic warming in these heat events. In terms of return period, for a one-in-10-year event, the magnitude of TNx30 in 2018 is estimated to be 1.7°C (1.7°–1.8°; 5th–95th) in the factual world, and 0.8°C (0.8°–0.9°; 5th–95th) in the counterfactual world (Fig. 2d). For a one-in-50-year event, the estimated magnitude of a heat event is 2.1° (2.0°–2.2°) and 1.2°C (1.1°–1.3°) in the counterfactual and factual worlds (Fig. 2d). The change in return level (0.9°C) between counterfactual and factual simulations is generally consistent with mean warming, as the shift in mean state between with (0.95°C) and without (−0.04°C) anthropogenic influence was 0.99°C (Fig. 2c). Besides, the uncertainty range of return periods increases with the rarity of events. We repeat our analyses by using different durations of either a 20-day or 40-day moving average and find similar risk ratio, suggesting the robustness of the results.

**CONCLUSIONS AND DISCUSSION.** Northeast China experienced a record-breaking nighttime heat wave in 2018 summer. This kind of 30-day nighttime heatwave was a one-in-500-year (or less) event in the counterfactual world. Forced by anthropogenic forcing and the observed 2018 SSTs, it became a one-in-60-year event.

This unprecedentedly long-lasting nighttime heat wave was also related to the northwestward shift of west Pacific subtropical high and the anomalous moisture transportation from the warm ocean. Additionally, the configuration of anomalous anticyclone

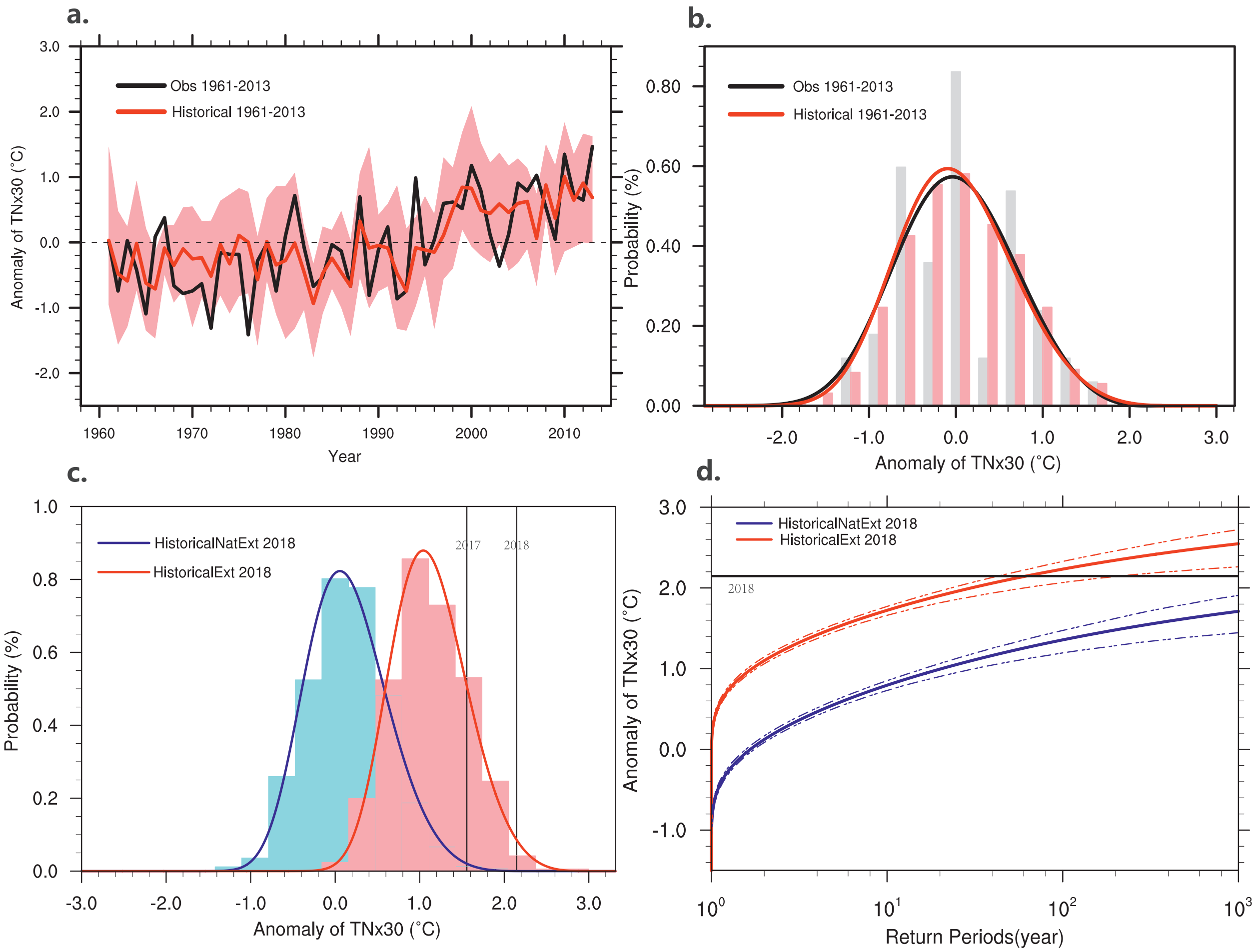


**Fig. 2. (a) Time series of observed (black) and simulated ensemble mean (red) of TNx30 anomalies, with 15-member spread shown as light pink shading. (b) Histograms and GEV-fit probability density function of TNx30 anomalies in observations (black line and gray bars) and historical simulations (red line and light pink bars) from 1961 to 2013. (c) Histograms and GEV-fit probability density function (PDF) of TNx30 anomalies in 2018 summer with 525-member HistoricalExt (red) and HistoricalNatExt (blue) simulations. The black lines indicate the TNx30 thresholds of 2018 and 2017. (d) As in (c), but for return periods. Dash-dotted lines indicate the 5th–95th uncertainty range based on 1,000 bootstrap resamples for all-forcing (red) and natural-forcing (blue).**

at 500 hPa over Northeast Asia during this heat event was reproduced with the six hottest simulations in study region (Fig. ES2), confirming the role of abnormal high pressure system in this heat wave event. As increased occurrence of anticyclonic circulations in the midlatitudes has made a substantial contribution (one-third to one-half) to the increased summertime temperature extremes over portions of Eurasia since 1979 (Horton et al. 2015), which leaves further questions as to whether anthropogenic warming has contributed to the heat waves like that in summer 2018 through affecting the background circulation. This study used an atmospheric model conditioned on the observed SSTs. Results are inevitably affected by uncertainty in the representation on the SSTs in the counterfactual world, especially for severe events with return periods greater than 50 years (e.g., Sparrow et al. 2018), and more work is necessary to better understand this uncertainty.

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